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EMBRACING IMPERFECTION FOR QUANTUM TECHNOLOGIES

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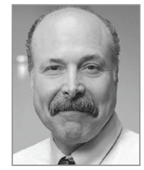


Christopher P. Anderson and David D. Awschalom

Solid-state spin qubits unlock applications in nanoscale quantum sensing and are at the forefront of creating distributed, long-distance entanglement that could enable a quantum internet.

You probably think something being defective makes it worse. Surprisingly, in the quantum world, defects in materials can be used as robust quantum bits, or qubits, that could fundamentally change the way we process, store, and distribute information. While undesirable in traditional semiconductor devices, lattice imperfections—including vacancies and impurities such as unwanted dopants—are now being harnessed for their unique quantum properties. In fact, they are leading candidates for developing potent quantum technologies, such as unlocking magnetic imaging at the nanoscale; for enabling a new internet of powerful quantum computers; and for creating unhackable communications secured by the fundamental laws of physics.

The irony that material imperfections are potentially ideal qubit candidates is not lost on the scientific community. For more than 50 years, the electronics industry has spent countless hours and resources trying to eliminate defects. They can affect the performance of everyday technologies like the processor chips in your computer and the integrated circuits making your car safe—potentially causing them to malfunction. Now those very same defects are being deliberately introduced into materials to create qubits with state-of-the-art quantum properties.

Defects come in a vast variety of forms.[1] The distinguishing features that can be harnessed for quantum technologies are the presence of unpaired electrons and multiple orbitals that those electrons can occupy. Electrons can undergo optical transitions between a defect's orbitals by absorbing and emitting single photons at specific wavelengths, which is why they are also sometimes called color centers. The emission can be measured using standard optical microscopy techniques—defects show up as luminescent dots in the crystal (see figures 1a and 1b).

Importantly, the electron undergoing optical transitions also possesses a magnetic moment whose spin-up and spin-down states act as a prototypical quantum two-level system—a qubit. The electron's spin state and orbital structure, and therefore its functionality, are defined by both the host crystal and the defect type (see figure 1c). Largely isolated and protected from their environment, the spin and orbital states are effectively embedded in a "semiconductor vacuum."

Defects as qubits gained prominence more than 20 years ago with the discovery of the many attractive

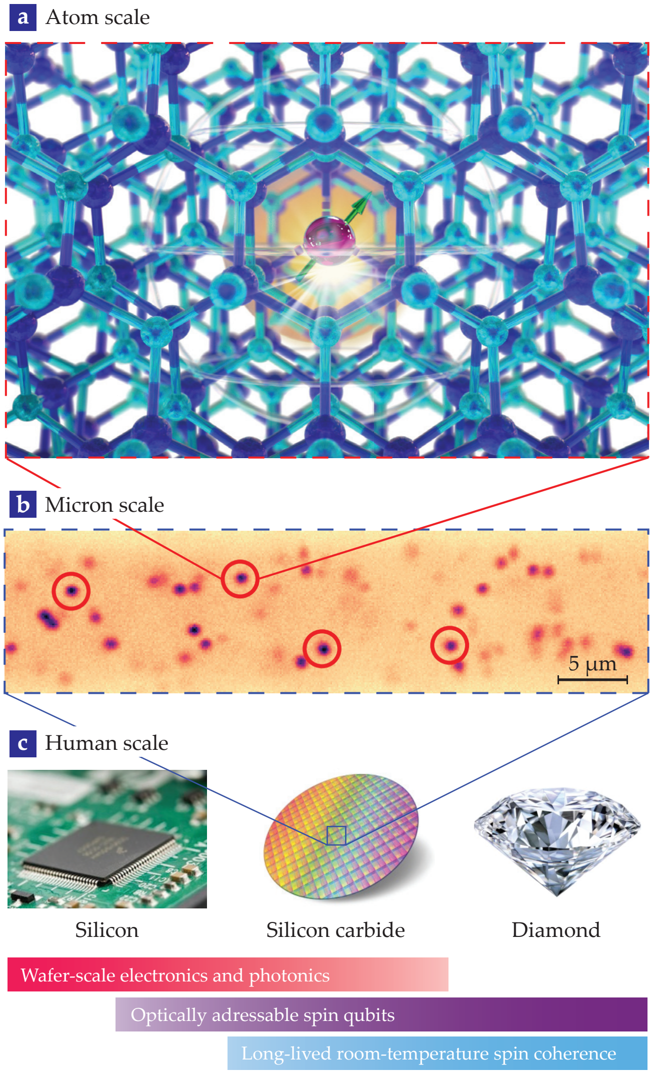


FIGURE 1. CRYSTAL DEFECTS AS QUANTUM BITS. (a) Schematic atom-scale representation of a defect spin qubit (glowing purple ball) in a crystal lattice. **(b)** In this micron-scale scanning photoluminescence measurement of isolated defects in silicon carbide, the circled dots are examples of confirmed optically addressable single qubits. (Adapted from K. Miao et al., *Sci. Adv.* **5**, eaay0527, 2019.) **(c)** Example host crystals for defect-based qubits are silicon, silicon carbide, and diamond. The colored bars indicate which systems display various desirable features.

features of the nitrogen–vacancy (NV) center in diamond, in which two adjacent carbon atoms are replaced by a nitrogen atom and a vacancy (see the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, Physics Today, October 2014, page 38). NV centers in diamond can store quantum information for extended periods of time, and the quantum state can be read out optically at room temperature. Those properties make NV centers an ideal platform for quantum sensing of pressure, temperature, magnetic fields, and electric fields. They have also been used to close loopholes in Bell's inequalities[2] and to perform rudimentary quantum error correction for quantum computation.[3]

The defect trifecta

Defect qubits combine three attractive features: They're spin based, they're optically active, and they're solid state.

Why spins? In the context of quantum information technologies, a qubit's lifetime and coherence time—how long its entanglement and superposition last—are everything. They put a fundamental upper limit on the number of logical operations that can be performed before the state is lost and set the sensitivity with which a quantum system can detect its environment. By those benchmarks, electron spins can be extremely robust quantum objects, potentially having lifetimes of hours and coherence times of seconds at low temperature. Even in noisy room-temperature environments, the coherence times can be longer than a millisecond, which is sufficient for most quantum applications. Additionally, the spin's energy can be easily tuned with static magnetic fields and its quantum state controlled by oscillating fields—the same spin-resonance techniques utilized in MRI, for example. In many ways, electron spins are "textbook" qubits, and high-fidelity control with off-the-shelf RF electronics is straightforward.

Why light? The linking of the spin magnetic moment to optical transitions is the key feature that distinguishes quantum defects in solids from other spin-based quantum technologies (see the article by Lieven Vandersypen and Mark Eriksson, Physics Today, August 2019, page 38, for comparison). That critical spin–photon interface, described in box 1, has important implications.

For starters, light allows for highly nonequilibrium, nonthermal spin polarizations. In other words, it enables efficient initialization of the spin into a particular quantum state even in "hot" environments. Spin transition frequencies are commonly in the gigahertz range, or millikelvin in units of temperature. So at room temperature, spins in thermal equilibrium are not polarized into a particular state. They are instead in a probabilistic, nearly equal mixture of spin-up and spin-down states. Even at the liquid-helium temperature of 4 K, spins are usually polarized only weakly, by less than 5%. Thermally initializing a spin qubit would require ultrahigh magnetic fields, to provide a large energy difference, or ultralow temperatures—constraints that greatly limit practical usage.

Light provides an alternative solution for qubit initialization. The high energy (hundreds of terahertz) of the optical transitions means the excited states are not thermally occupied, and laser-driven, spin-dependent optical processes can produce ground-state spin polarizations approaching 100% even at room temperature. The coupling to light is what makes quantum operation possible at elevated temperatures, since initializing the qubit into a known state is the essential first step in all quantum protocols.

Optical transitions also enable the accurate, deterministic readout of the quantum state. Because the magnetic dipole moment of a single spin is small, it couples only weakly to its environment, making spin a difficult quantity to measure directly—doing so requires extremely low temperatures, high fields, and complicated device integration. On the other hand, using suitable optical transitions can make readout of single spins easy; it can even be a demonstration for teaching purposes in introductory undergraduate physics labs. That ease (not guaranteed for all defects) arises from the specific quantum mechanical selection rules for the allowed transitions of the spin–photon interface. Importantly, the interface also un-

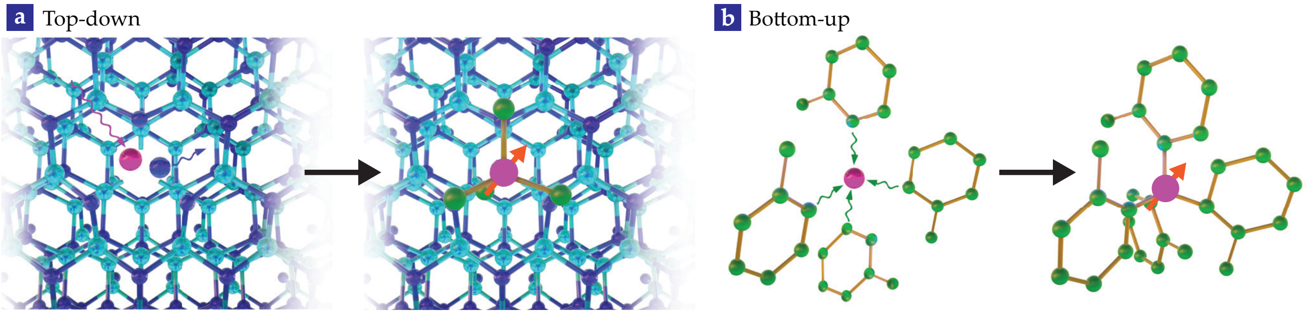


FIGURE 2. CREATING DEFECT SPIN QUBITS. (a) Most spin systems today are created with a "top-down" approach where impurities or vacancies are introduced into an existing structure. Here, an impurity (magenta) is introduced into a lattice, displacing an atom (blue) from a lattice site. The impurity and vacancy together can function as a qubit. **(b)** A "bottom-up" approach instead builds the entire structure atom by atom. Schematically, a central ion (purple) can be coordinated with specific chemical ligands (green) to create a structure with the desired behavior.

locks the ability to entangle single electron spins with single photons (see box 1).

Finally, the weak, short-range dipolar interaction between spins makes coupling two spins together difficult. Thanks to the spin–photon interface, light provides an alternative for the long-range "wiring" needed for spin qubits to communicate with each other and with other quantum systems. Because the real power of quantum technologies comes from connecting and entangling many qubits, such long-range interactions are essential. Photons are also the ideal transmitters of quantum information: They travel at the speed of light, can be guided in low-loss optical fibers, and are noise-free at room temperature. Excitingly, such light-mediated entanglement of distant defect-based qubits to form rudimentary quantum networks has

Box 1. The spin–photon interface

While the spin-up and spin-down ground states of a solid-state defect form the basis for a qubit, it is the optical transitions between those ground states and higher-energy orbitals that enable qubit preparation, readout, and coupling between qubits.

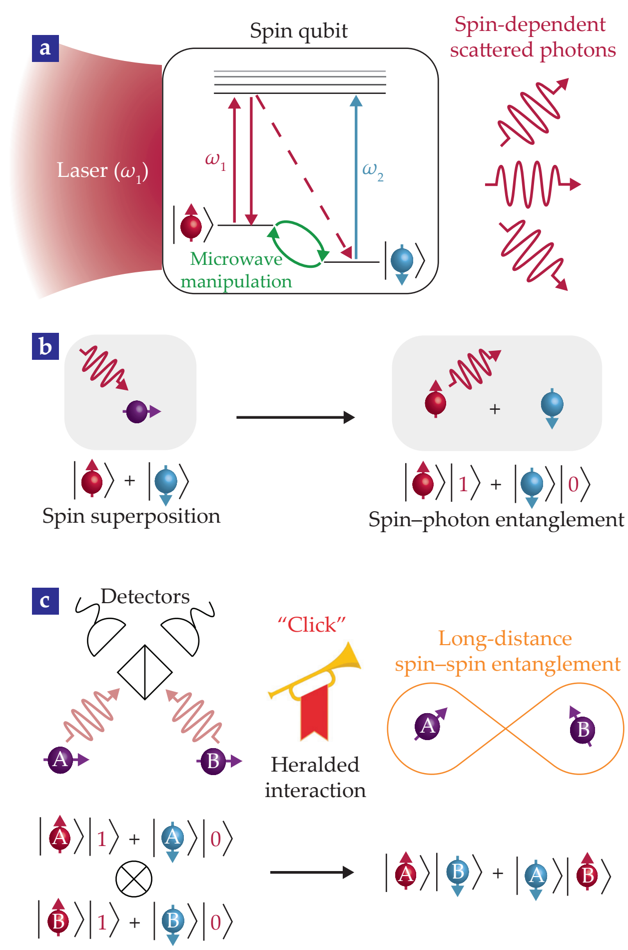
Spin-selective optical transitions between the ground state and excited states allow for spin-dependent photoluminescence and state readout, as sketched in panel a. Here, the frequency ω_1 that will optically excite a spin-up electron (red) will not excite a spin-down electron (blue). The excited defect will emit light when it relaxes, so the detection of scattered photons indicates that the spin is up.

Spin-state preparation is achieved by pumping the defect with a laser tuned to frequency ω_1. An optically excited spin-up qubit has a finite probability of flipping (dotted red line) as it returns to the ground state. Once the qubit is spin-down, the laser is no longer resonant, and the state is stationary. Therefore, after sufficient pumping, the qubit has a nearly 100% probability of being spin-down. Microwave signals (green) tuned to the energy separation between spin states can manipulate the qubit state using common electron spin-resonance techniques.

In this example, the spin dependence comes from frequency selectivity, but more generally a spin–photon interface can be selective based on any property of light, including polarization.

Panel b illustrates how spin-selective optical absorption can transform a spin superposition state (purple, left) into an entangled state between the spin and the presence (1) or absence (0) of a single photon. Because only the spin-up state couples to incident light at ω_1, a photon is created only when the spin is up.

Photons emitted by the spins can mediate long-range interactions, as sketched in panel c. Consider two spatially separated spin qubits that, using the scheme in panel b, are entangled with their emitted photons and have the same frequency. Interference at a 50:50 beamsplitter and subsequent detection ("click") of a single photon will announce, or herald, the creation of entanglement between the distant spins. As a result of the measurement, the initial pair of entangled spin–photon states is transformed into an entangled state of just the two spins.



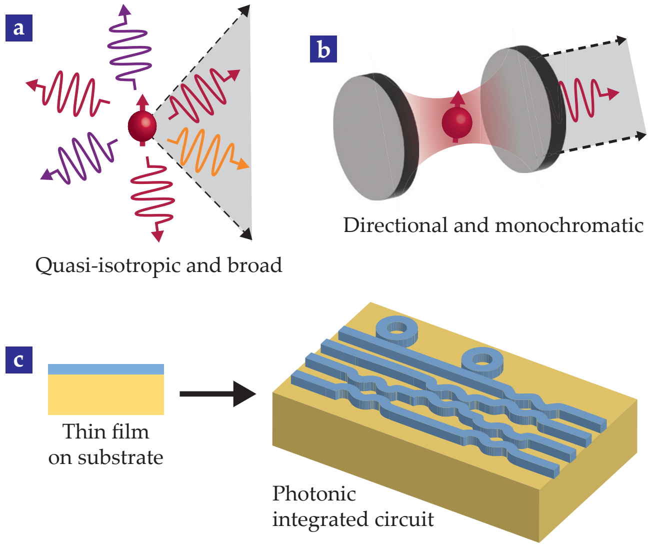


FIGURE 3. PHOTONICALLY ENHANCED QUBITS. (a) In free space, defect-based single-photon sources tend to emit in many directions and have a wide spread of emission frequencies (different colors). Only a small fraction of the emitted light is collected (gray cone). **(b)** The emission behavior can be enhanced by integrating the source into an optical cavity, schematically displayed as two mirrors. Photon emission gets funneled into the cavity mode, dramatically decreasing the frequency spread and increasing the useful light collected. **(c)** Integrated photonic devices can be created by starting with a high-quality thin film of the desired qubit-hosting material (blue) bonded to a substrate (yellow) with lower index of refraction. The top layer can be patterned into photonic integrated circuits that contain the necessary components—cavities, beamsplitters, phase shifters, and so on—to perform quantum optics experiments on a chip.

recently been demonstrated.[4] In a sense, defects provide built-in strong coupling between the spin and light degrees of freedom and thus enable efficient translation of quantum information across disparate frequencies.

Why solid state? Hosting quantum states in a solid material gives unique advantages. First, the power and scalability of semiconductor technology can be tapped to naturally embed qubits in devices fabricated from the host material. For example, micro- and nanofabricated devices that control photons, phonons, or charges can be used to manipulate, protect, or couple qubits. Second, scientists can create and manipulate isolated qubits without the ultrahigh vacuum or ultrastable lasers typically used in trapped-atom and trapped-ion experiments. As a result, defect-based quantum systems and devices can be small, portable, and usable in ambient environments—desirable traits for practical quantum devices for the real world.

As an added benefit of working with solid-state systems, the electron spin states of defects can couple to nearby lattice atoms that, because of their isotope, have a net nuclear magnetic moment. Such nuclear spins in solids are perhaps one of the most robust quantum memories known to science, with coherence times of minutes and lifetimes that can exceed days.[5] Local multiqubit entangled registers of single electrons and nuclei have been created in a multitude of solid-state defect-spin platforms.

The combination of scalable fabricated devices, long-lived spin states, and light-based initialization, readout, and mediation of interactions is what sets defect qubits apart. For example, the ability to engineer systems in an integrated, solid-state platform allows for unprecedented control of the magnetic, electrical, and photonic states of the qubit needed to optimize performance. Just like how the modern information age uses magnetic states (for longevity) in hard drives to store data, light (for speed and bandwidth) to communicate, and semiconductor devices (for scalability and size) to compute, defects in solids similarly leverage the same advantages for quantum technology.

Beyond the NV center

Over the past two decades, the field of quantum information has expanded greatly, and scientists now have a broad range of quantum systems at their disposal—they can choose which qubit to employ based on their needs and the specific quantum application. Atomic physicists, for example, can select from several different atoms and ions from the periodic table. Meanwhile, superconducting systems have evolved beyond the first charge qubits and now offer an impressive variety of artificial two-level systems, each with unique protections from noise. Such advances in quantum science have arisen from a pioneering spirit to discover new platforms and to understand the underlying fundamental physics to mitigate or even circumvent shortcomings in performance. In the same way, the field of defect-based spin qubits has expanded beyond the originally discovered NV center in diamond, as illustrated in figure 1c.

In the search for new and better qubits, a physics-based understanding of the desired properties of solid-state defects has served as a guide for more than 20 years.[6,7] The widening of the field's scientific scope beyond the NV center resulted in the discovery of optically addressable defects in silicon carbide[8] (see PHYSICS TODAY, January 2012, page 10). Those defects act almost in direct analogy to NV centers in diamond. In particular, they have the features previously thought unique to the NV center: room-temperature initialization and readout of single electron spin states with long coherences. In addition, SiC has many of the desirable properties of diamond, including hardness, stiffness, optical clarity, high thermal conductivity, and a high index of refraction. As a result, SiC is used as a substitute for diamond both in jewelry and in industrial applications such as abrasives.

Where SiC really shines, however, is as a technologically mature, wafer-scale semiconductor; it is used for components in electric cars, 5G technologies, and LED light bulbs. Billion-dollar SiC fabrication facilities have opened in the past year that can produce wafer-scale, quantum-grade single-crystal materials. Besides clear cost and scalability advantages over diamond, SiC is also a much easier material from which to fabricate useful quantum devices. In fact, SiC is compatible with the same CMOS fabrication techniques that are used by the semiconductor industry to make today's microchips. Quantum states in SiC can be readily integrated into the mechanical resonators found in a cell phone, into electrical devices to read out their quantum state in new ways, and into low-loss photonic circuits to create efficient entanglement, among other potential applications.

All the key quantum functionalities have been demonstrated in SiC over the past 10 years or so: single-qubit creation, high-fidelity control, nuclear-spin quantum memories, device integration, single-shot quantum readout, and record-long coherence times.[9] In many ways, SiC has caught up with or exceeded

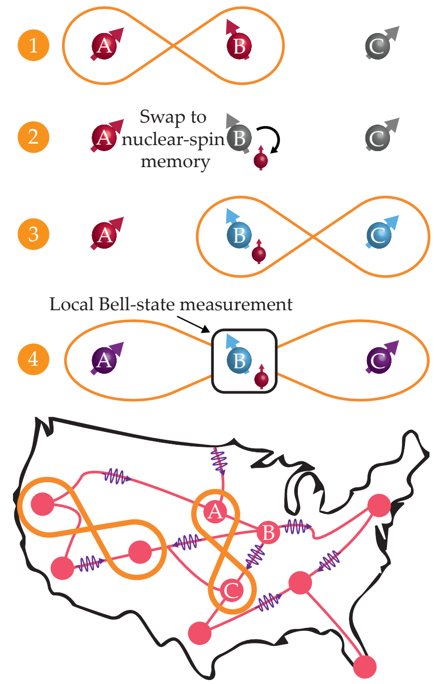
Box 2. Enabling long-range quantum networks with defects

Any future long-range quantum network will require quantum repeaters to prevent information loss. Solid-state defects can implement such a quantum repeater via a four-step protocol:

1. Defects A and B are entangled (denoted by the orange lemniscate) using the photon-brokered interaction described in box 1.
2. Defect B's half of the entangled state is swapped into a long-lived nuclear-spin quantum memory.
3. Defects B and C are entangled. Even if the interaction fails, the entanglement from step 1 is preserved by the quantum memory and the entanglement can be attempted again.
4. A local two-qubit measurement (called a Bell measurement) of the electron and nuclear spins at B "fuses" the separately entangled pairs (red and blue) and creates an overall entanglement between defects A and C (purple).

The quantum repeater node at B obviates the need for direct, coherent transmission between A and C; it instead breaks up the quantum link into independent segments and allows entanglement to be created even though A and C never directly interact.

Such defect-based repeaters could form the backbone of long-distance quantum networks, thereby enabling a distributed internet of entangled quantum devices. Quantum nodes could be linked by light sent over a fiber-optic network, sketched here as red circles and lines. The defects described above, for example, could be located in the nodes labeled A, B, and C.



the performance of NV centers in diamond—exemplifying the power of searching for qubits in new materials.

Scientists have since expanded their search to include new types of defects in diamond, in silicon,[10] and even in two-dimensional materials such as hexagonal boron nitride.[1] The unique properties of these new host materials and defects have driven many of the major advances in the field. Understanding the vast interplay between the desired application, host crystal, and defect structure underpins a recent "blueprint" for quantum materials science with defects[11] and a new "periodic table for quantum coherence."[12] For example, calcium tungstenate ($CaWO_4$) was predicted and recently shown to have record-long spin coherence times for a naturally occurring crystal. It's also part of a broad trend of repurposing traditional laser crystals, including rare-earth-doped oxide materials, for quantum applications. In fact, many of the features that make a good gemstone—including a high index of refraction, optical clarity, and hardness—are exactly the features one wants in a host of solid-state defects.

Most solid-state defect qubits are made with a "top-down" approach, in which a crystal host is implanted or irradiated to create impurities or vacancies, as shown in figure 2a. Those processes make it difficult to place qubits in desired locations and may cause unwanted damage to the crystal, which results in reduced coherence. Tackling those challenges is an ongoing area of research. Furthermore, top-down approaches are subject to fundamental design limitations set by thermodynamics, crystal symmetries, commercial availability of the crystals, and more.

One emerging alternative is to build optically active solid-state spin systems from the "bottom up," as shown in figure 2b. Instead of removing atoms or adding single impurities to a host, one can use the power of synthetic chemistry to assemble a quantum system atom by atom. For example, researchers have designed transition-metal molecular complexes with optical transitions, and by changing the ligands in the complex they tuned the spin and optical properties.[13] A bottom-up strategy has even been used to tailor the level structure in molecular complexes to increase quantum coherence times. Finally, molecular complexes displaying coherent and narrow optical emission have also been demonstrated. Although relatively new, bottom-up approaches could offer unparalleled flexibility and potentially allow for single-molecule quantum devices designed with a particular quantum application in mind.

Photonic integration

Coupling to light is a distinguishing feature of solid-state defect-based quantum systems. Defects in solids, however, are not ideal single-photon sources. Photon emission is commonly disturbed by phonons, can be plagued by competing nonradiative relaxation pathways, or may be affected by nonidealities in the energy-level structure outlined in box 1. In some cases, the optical lifetime—the delay before a photon is emitted—can be so long that the qubit shines too dimly to be practically measured. In addition, the qubit is much like a light bulb: It radiates photons in all directions. If those photons contain information one wants to sense or they are mediating an interaction with another qubit, one does not want them to emit randomly (see figure 3a). Creating devices that enhance or guide the optical emission from defect spin qubits is therefore critical.

Luckily, there is a solution to all those problems at once. Edward Purcell noted in the 1940s that the spontaneous emission of a two-level system can be modified by embedding it inside a resonant circuit or cavity (see figure 3b). The resonant structure modifies the possible states that the system can emit light into, and it causes preferential channeling of photons into a single spatial and spectral mode defined by the cavity. This "Purcell effect" can also increase the emission rate, thus creating a brighter and purer source of single photons. Purcell noted that for the effect to be prominent, the cavity must be both small and low loss. The natural integration of defect-based qubits into a solid-state material is thus a major benefit, since the material's high index of refraction can confine light at the nanoscale.

High-quality nanoscale optical resonators with embedded defects can be created using the same technique that dominates the integrated-photonics industry: a thin film of material, usually silicon, on top of a substrate, often silicon dioxide, that has a lower index of refraction. For example, thin films of both SiC and diamond on oxide have recently been developed. Through subsequent simple vertical etching, one can make waveguides—essentially wires for light—that are surrounded on all sides by lower-index media, as shown in figure 3c.

Nanofabricated photonic devices have other advantages as well. For example, detectors, laser sources, and even linear optical elements such as beamsplitters can all be fabricated on a single chip. By combining this capability with nonlinear optical frequency conversion and electro-optic tunability of some materials, one can harness the full power of integrated photonics and achieve powerful quantum functionality. Nonclassical squeezed states of light could be created in the same resonator that hosts single-photon emitters, for instance. Defects can also potentially be sources of highly entangled states of light called cluster states, which can form the basis of measurement-based quantum computation, in which quantum algorithms are implemented via a series of single qubit measurements.

Mitigating noise

While some defects make robust qubits, not all imperfections are desirable for quantum applications. Unwanted lattice defects, extra charges, and uncontrolled spin magnetic moments can introduce noise that disturbs the quantum state. The spin ground state of a defect qubit is predominantly sensitive to nearby nuclear and electron spins in the host crystal, which cause fluctuating magnetic fields that limit qubit coherence. On the other hand, the coherence of single-photon absorption and emission, which sets the fidelity of state preparation and readout and of long-distance entanglement generation between spins (see box 1), is degraded by electrical noise, which arises naturally from the movement and fluctuations of electrons and holes in the solid. Electrical noise is especially challenging in fabricated devices with nearby surfaces that can trap charges.

For magnetic noise, purifying the host material so that it contains only specific isotopes with no nuclear magnetic moment has greatly increased coherence, which improves quantum sensing protocols and boosts quantum memory times. Spin qubits can also be made insensitive to magnetic noise by engineering energy levels so that they do not shift with external perturbations. In addition, one can protect coherence by using dynamic quantum control to rapidly flip the quantum state and produce a noise-cancellation effect known as a spin echo. A combination of such techniques recently achieved coherence times exceeding five seconds in SiC—the longest ever demonstrated for an electron spin in a solid, sufficient for nearly all desired quantum applications.[9]

Because light-based interactions are key to applications of defect spin qubits, combating electrical disturbances that degrade photon coherence is a priority. For diamond, there has been a pivot away from the established NV center toward vacancy centers involving silicon, germanium, and tin. The main advantage to using those group IV–based defects is inversion symmetry: The system is nonpolar and insensitive to electric fields to first order. That simple change has yielded dramatic improvements—robust single-photon emitters can be integrated into nanophotonic cavities and display highly coherent emission of light coupled strongly to the optical mode of the cavity.[14] For SiC, one can use doping to create a simple electrical diode, which has a depletion region that is completely devoid of free carriers and thus of fluctuating charges. The depletion region therefore eliminates electrical noise, resulting in near-perfect, highly tunable quantum emission.[15] Such doping control is simply not feasible in diamond, which highlights the unique advantages new materials can provide.

Those examples illustrate the two strategies to combat noise on a qubit. One is to eliminate the source of the noise. That can sometimes be achieved with careful materials engineering, but it has stringent fabrication requirements. The other is to create a qubit that is insensitive to the noise source. In doing so, however, the qubit also becomes insensitive to many tuning knobs that are needed to control the system. The most appealing approach will likely be a combination of the two so that the qubit operates in a "Goldilocks zone" of sensitivity and controllability.

Maturing technologies

The past decade's advances in quantum information science and engineering with solid-state defects have been largely the result of a shift in mindset—toward exploring new qubit candidates in new materials and expanding the range of applications. In the future, a diversity of approaches is likely, which reflects the varied applications that defects can tackle. The development of new platforms requires a multidisciplinary approach that involves materials science, atomic physics, condensed-matter physics, electrical engineering, and advances in nanofabrication. In fact, linking with the very semiconductor industries that have worked to eliminate defects may be the key to scaling defect-based quantum systems.

Even as they have been the subject of much ongoing research, defect-based quantum states have started to enter the mainstream for core quantum applications: sensing, computing, and communications. Much of the leading technical work was demonstrated using the NV center in diamond, from small-scale error correction[3] to a lab-scale three-node quantum network that can teleport quantum states.[4] NV centers have been commercialized into scanning-probe nanoscale magnetometers, which have been used to measure fundamental condensed-matter phenomena.[16] They have also found use as biosensors[17] (see Physics Today, August 2011, page 17) and as room-temperature vector magnetometers for navigation and geoscience.

Although they can find use in all the major areas of quantum science, solid-state defects really shine in two critical applications: room-temperature quantum sensing of magnetic fields and long-distance quantum communications and networking. For quantum sensing, major efforts focus on optimizing near-surface qubits, which can sense the environment more readily than deeper qubits but are subject to noisy interfaces. For quantum networking, the main hurdle is efficient mediation of long-distance entanglement between qubits, which is limited both by the quality of optical devices and by the noisy photon emission that results from integration into those devices.

A tantalizing goal on the horizon is a quantum internet,[18] which, in analogy to the classical internet we know today, would link quantum devices and distribute quantum information. It would, for example, enable more powerful, modular quantum computers, distributed quantum sensing of gravity, and quantum key distribution over global scales. (For more on quantum key distribution, see the article by Marcos Curty, Koji Azuma, and Hoi-Kwong Lo, Physics Today, March 2021, page 36.) The 2022 Nobel Prize in Physics was awarded for work with spatially separated entangled photons (see Physics Today, December 2022, page 14). Creating such entanglement at the metropolitan scale or larger, however, will require quantum repeaters to mitigate photon loss. These repeaters each combine a spin–photon interface with a long-lived quantum memory (such as a nuclear spin) to break up a quantum channel into multiple shorter links. By buffering signals using the quantum memories, entanglement swapping efficiently links the end nodes, as described in box 2.

Defects in solids provide all the necessary components to implement quantum repeaters and create a scalable quantum network backbone: Photons are the natural choice for quantum communications, spins are robust memories, and semiconductors are scalable. Such a backbone is the focus of recent large industrial efforts, quantum startups, and national and international collaborations of government labs and universities. In the future, we envision rack-mounted cryostats stashed in closets across the country, with defect-based devices interfaced with fiber-optic cable to route quantum entanglement for sharing secure cryptographic keys, distributing quantum computation, and making more powerful sensors.

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